

# Recent Development and Validation of Geant4 Hadronic Physics

Julia Yarba, Fermilab

On behalf of Geant4 Hadronic Group

CHEP 2012, New York City, NY

05/22/2012



## Outline

- Introduction to Hadronic Physics in Geant4
- Current Key Developments
  - Fritiof string model (FTF)
  - Bertini Cascade (BERT)
  - Precompound and deexcitation (Preco)
  - High Precision low energy neutrons (HP)
  - Capture and annihilation
- Other Available Models
- Validation
- Summary



## Introduction to Hadronic Physics in Geant4

- Physics models = final state generators
- Physics process = cross section + final state model
- Physics list = list of processes for each particle
  - Hadronic models are valid over finite energy ranges → register several processes in a list, overlaps in energy
  - Several lists in Geant4, choice depends on the application
  - Evolution:  
LHEP -> QGSP -> QGSP\_BERT "family" -> **FTFP\_BERT**



## Fritiof (FTF) String Model

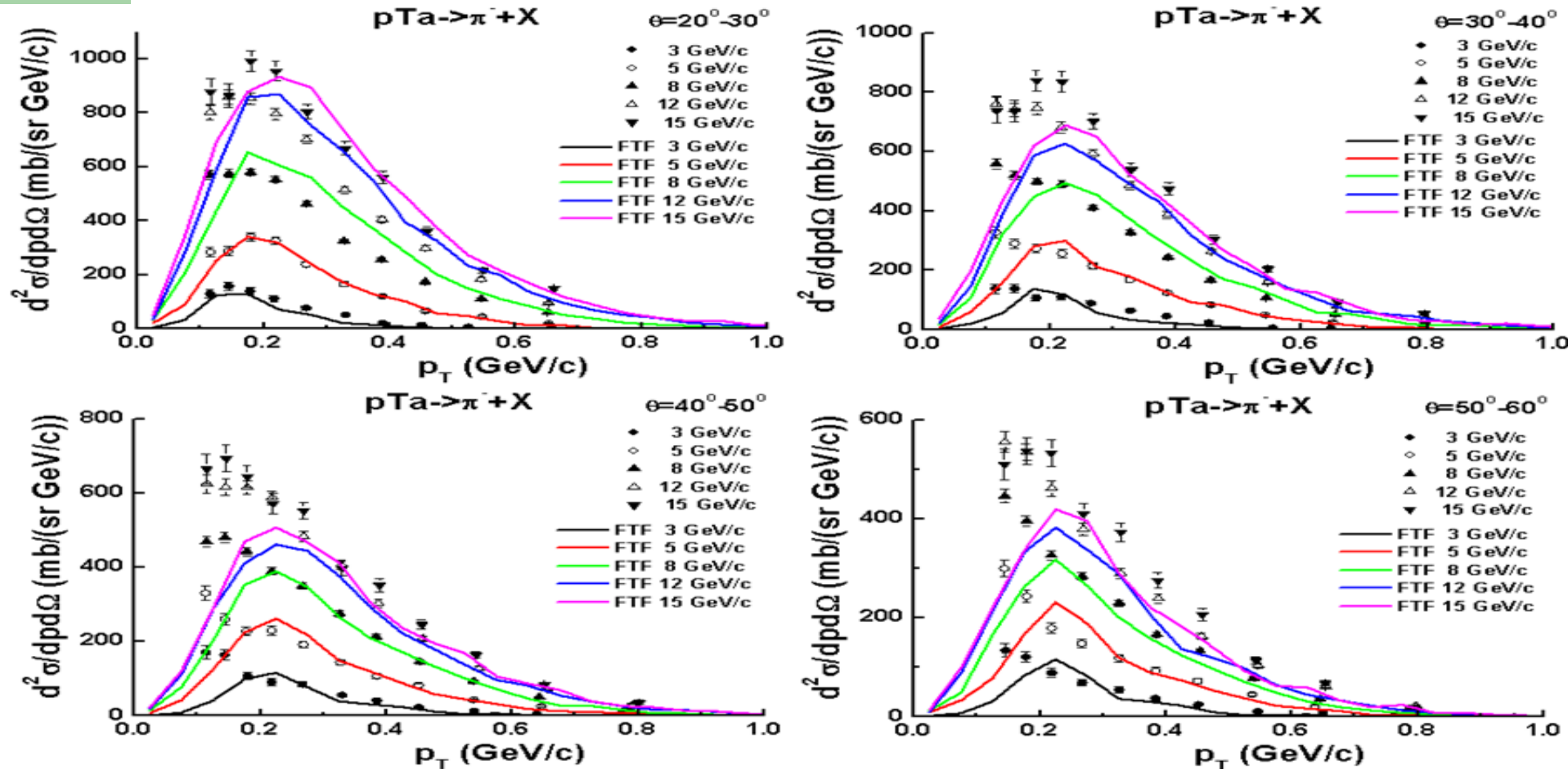
- Simulates hadron-hadron, hadron-nucleus, and nucleus-nucleus interactions
  - Valid in 3GeV-1TeV
  - When modeling hadronic showers, important for
    - Energy response
    - Energy resolution
  - Interest renewed several years ago, after discovering QGSP-related discontinuities in calorimetric energy response vs beam energy
- Note: In the core of several MC generators (HIJING, ART, UrQMD)

## FTF Development Highlights

- Addition and tuning of Reggeon Cascade
  - Cascading as a repeated exchange of quarks between nucleons
  - Allows better nuclear destruction/de-excitation after the initial high energy interaction
- Improved low mass string formation (add quark exchange) and fragmentation
- Interfaces smoothly with cascade models (BERT)
- Tuning and Validation with HARP-CDP data
- Extension to anti-matter: anti-baryons (more later), light anti-ions

## FTF Validation – HARP-CDP data

A. Bolshakova et al., Eur. Phys. J. C63 (2009) 549-609

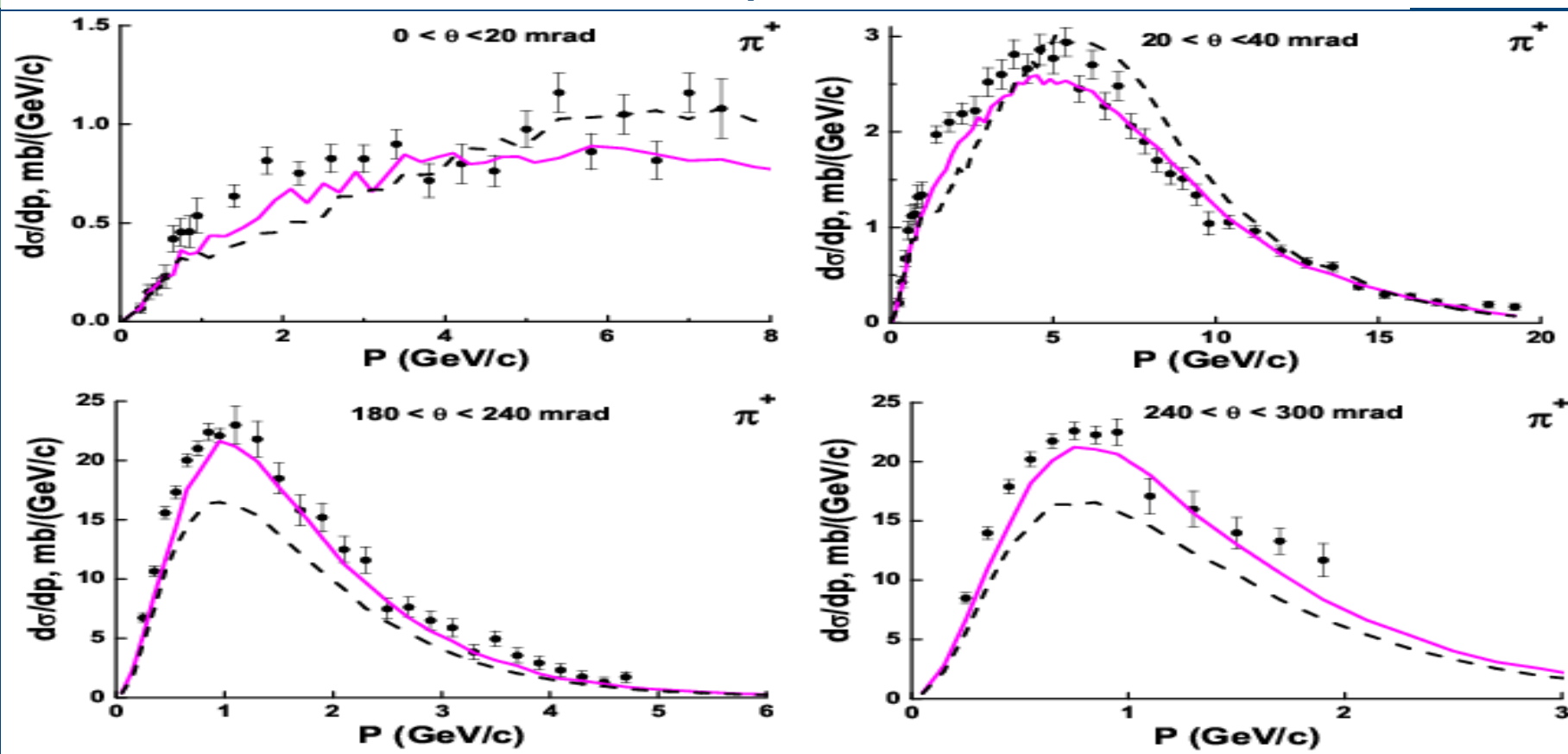


## FTF Validation – NA61/SHINE data

N.Abgrall et al., Phys. Rev. C84 (2011) 034604

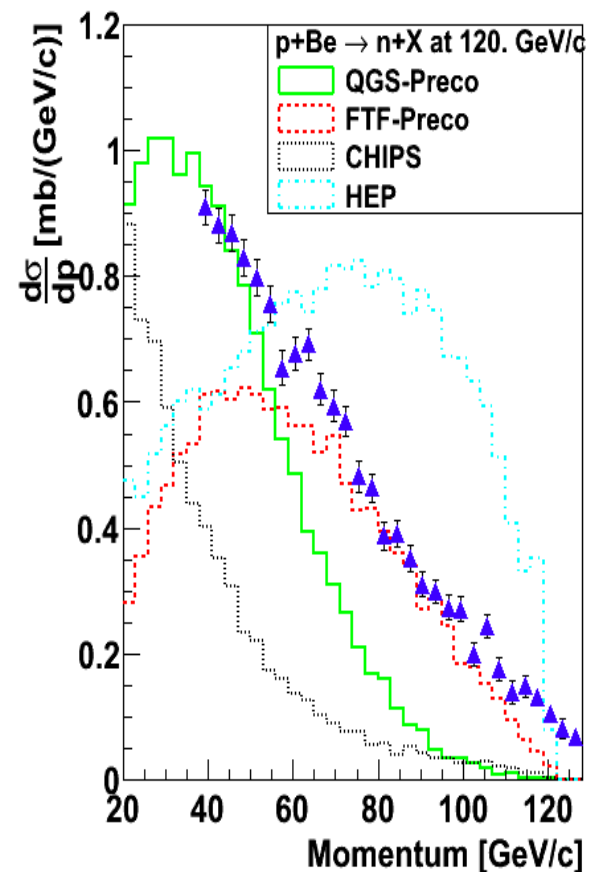
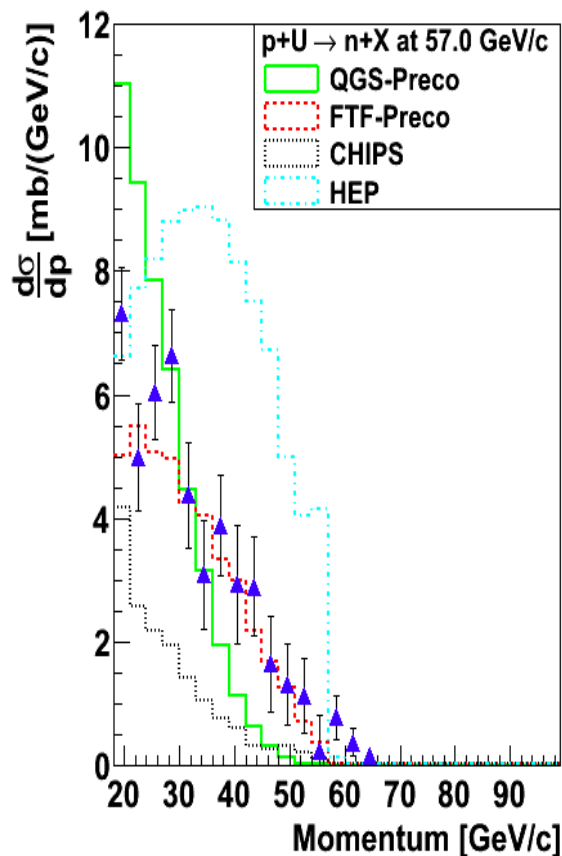
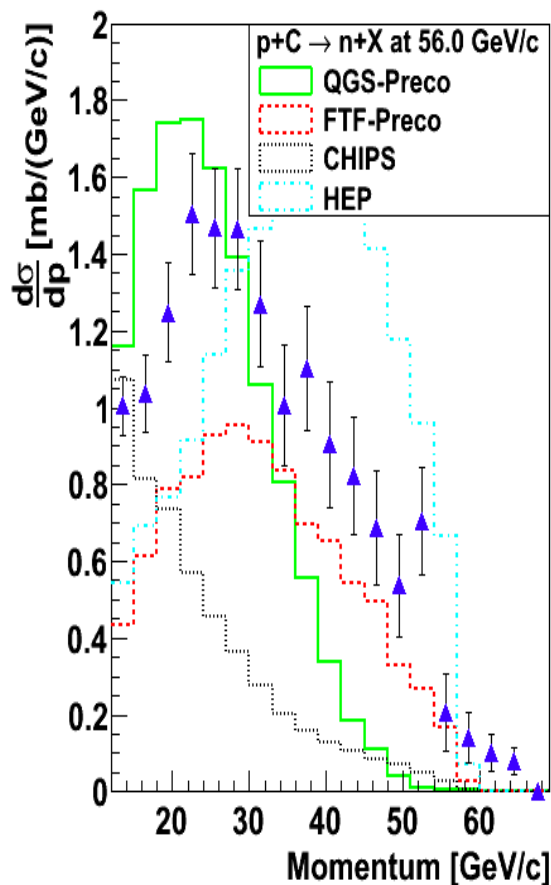
FTF improvement between G4.9.2 (---) and G4.9.4 (—)

31GeV/c p on C  $\rightarrow \pi^+ + X$



## FTF Validation – MIPP data (FNAL-E907)

T.Nigmanov et al., Nucl.Instrum.Meth.A598:394-399,2009







## Bertini (BERT) Intranuclear Cascade

- Geant4 adaptation of earlier code (1960s)
- Valid for p, n, pi, K, hyperons of  $E_{kin} < 10 \text{ GeV}$
- Precompound and evaporation:
  - Its own internal version
  - Interface to Geant4 Precompound model
- Important for
  - Energy response and resolution
  - Shower lateral profile
- Extensively validated with data from thin target experiments

## BERT Development Highlights

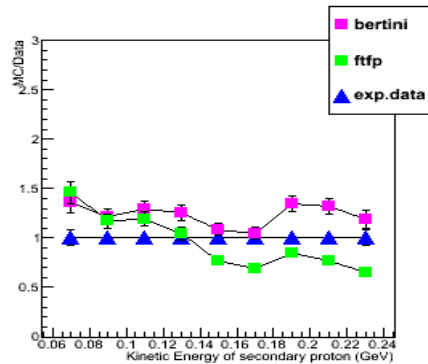
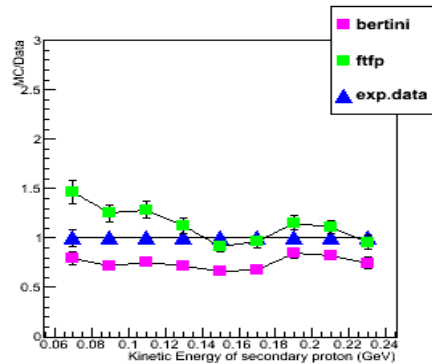
- Revision of internal cross sections
- Added trailing effect
  - Local density reduction in nuclear medium following an individual scatter within nucleus -> predicts fewer final state nucleons
- Re-scattering from string models
  - High energy scatter on nucleon produces fragments either inside or outside the target nucleus
- Incorporated gamma-nucleon interactions
- Support of capture processes (more later)
- Significant code structure improvement

## BERT vs FTF at 5.0-7.5GeV/c

Yu.D. Bayukov et al., Sov.J.Nucl.Phys.42:116-121,1985

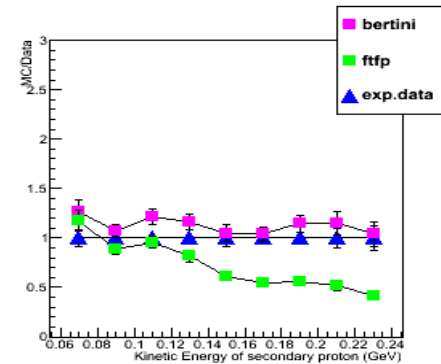
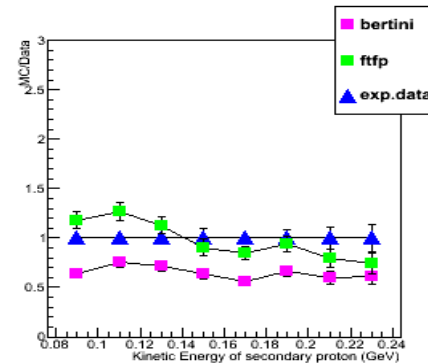
7.5GeV/c p on C or U

KE of secondary p at  $\theta=59.1$

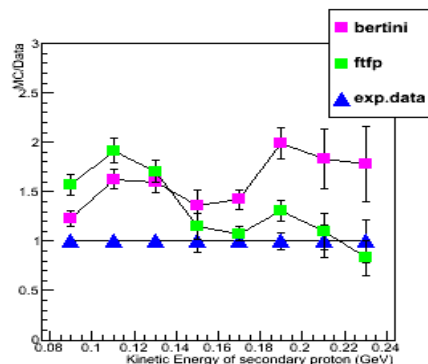
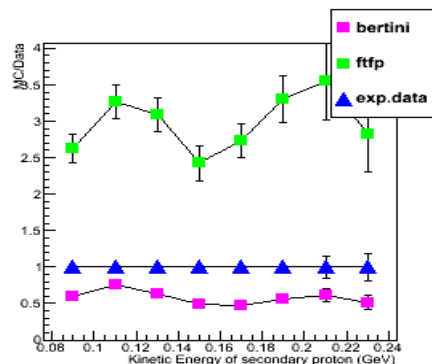


5GeV/c pi+ on C or U

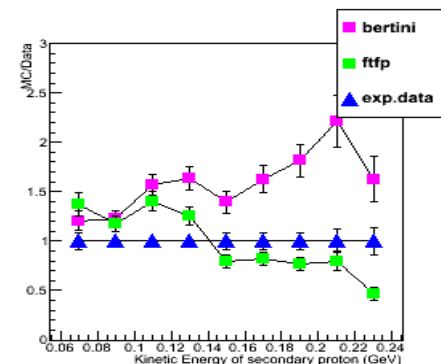
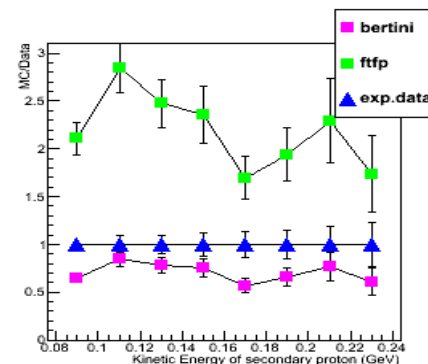
KE of secondary p at  $\theta=59.1$



KE of secondary p at  $\theta=119.0$

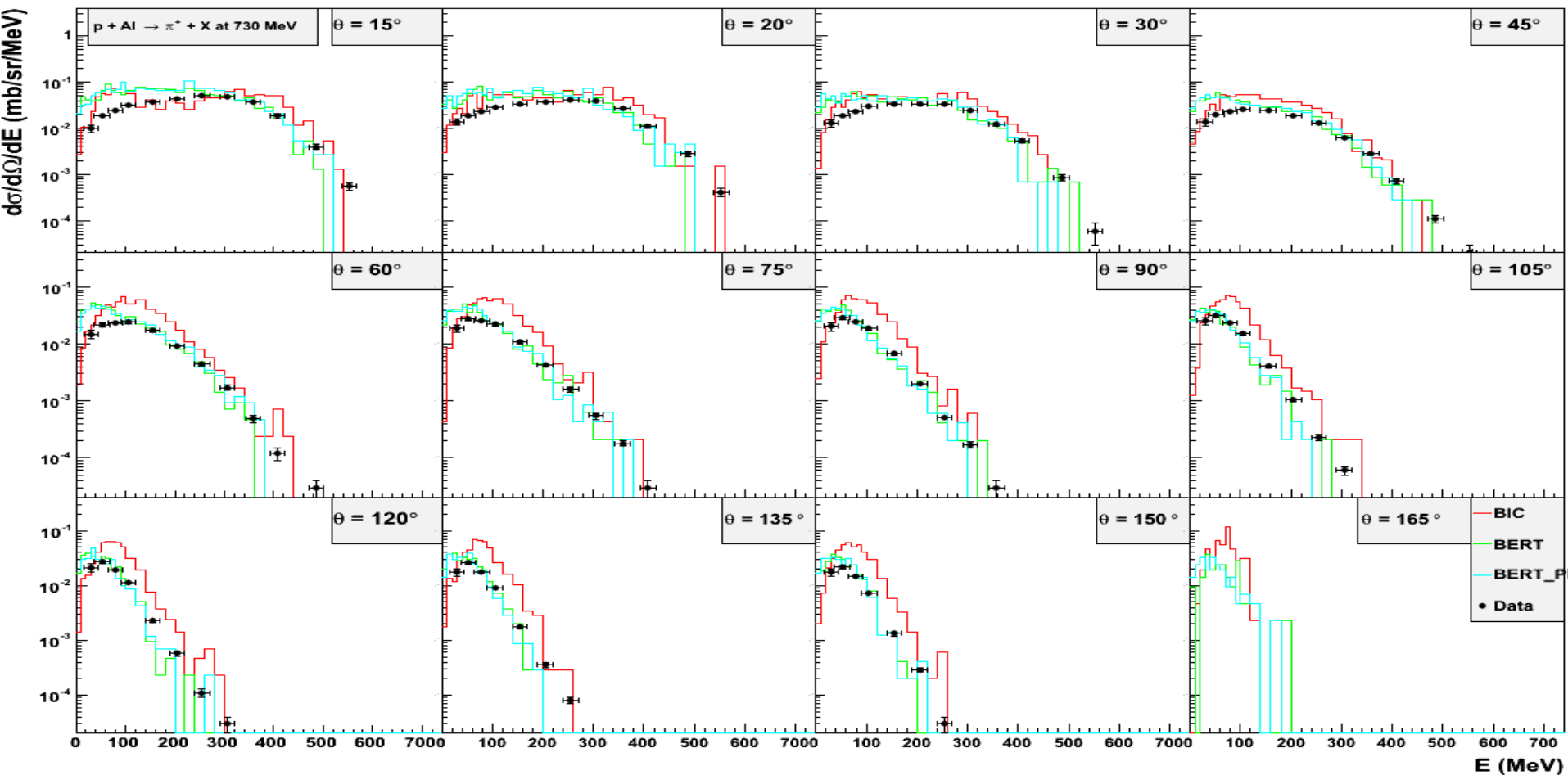


KE of secondary p at  $\theta=119.0$



## BERT at 730MeV – IAEA benchmark

<http://www-pub.iaea.org>



## Precompound/Evaporation Model

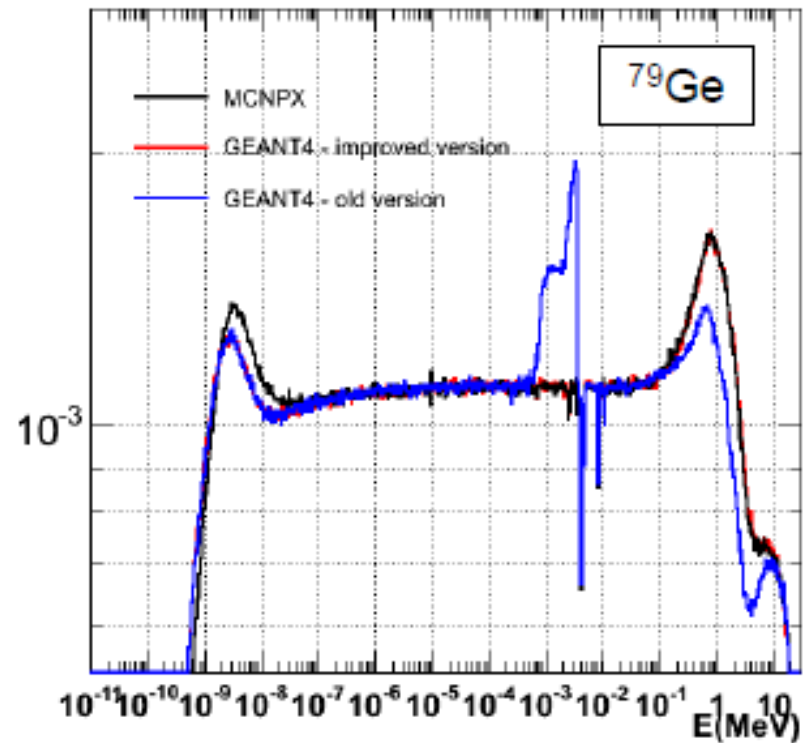
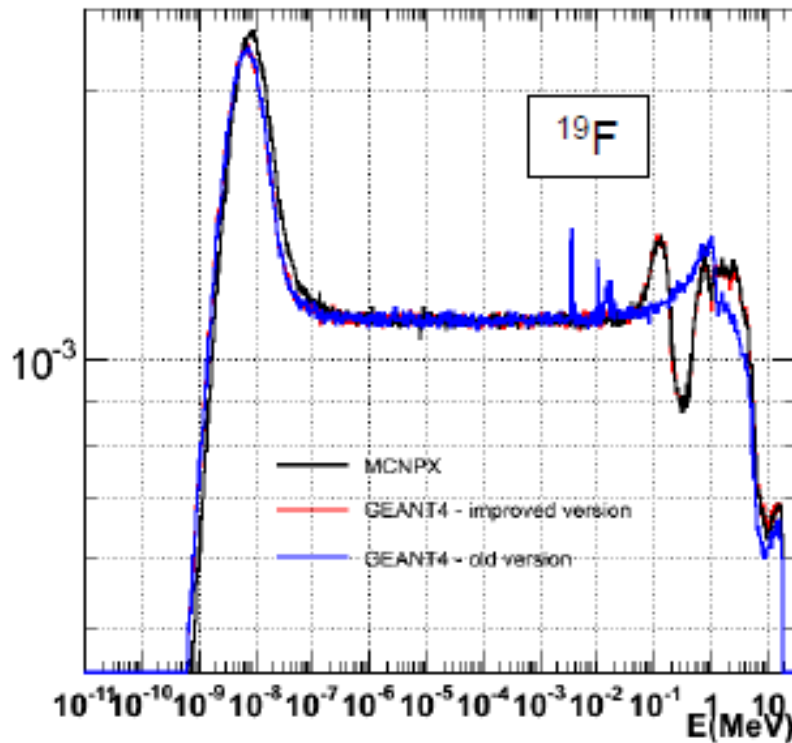
- Valid for any excited nucleus
- Important for
  - Energy resolution and energy response
- Precoumpound
  - Particle emission vs internal transition between exciton states
  - Revised transition probabilities and exit conditions
- De-excitation processes revised
  - Fission
  - Fermi breakup (light nuclei)
  - Weisskopf-Ewing Evaporation: n, p, D, He3, alpha
  - Photon evaporation
  - New GEM to emit heavy fragments ( $Z < 13$  and  $A < 29$ )

## High Precision (HP) Low Energy Neutrons

- Data-driven neutron transport at  $E_{kin} < 20 \text{ MeV}$
- Important for
  - Better lateral profile of hadronic showers
  - Time dependent hadronic showers development
  - Background radiation study
- Interface to updated ENDF library
  - Cross sections for neutrons on isotopes
  - Reaction final state products
  - More isotopes included (395 vs 181 in earlier version)
- Benchmarking and extensive validation underway

## HP comparison vs MCNPX

Recent improvements bring Geant4 into very good agreement with MCNPX

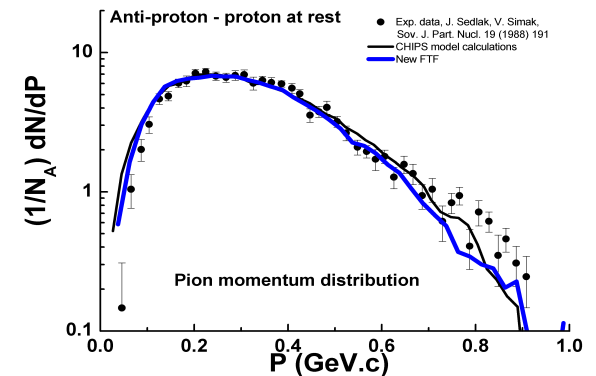
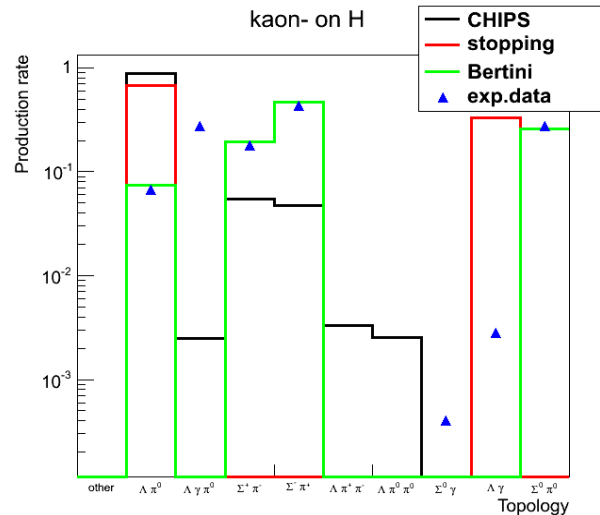
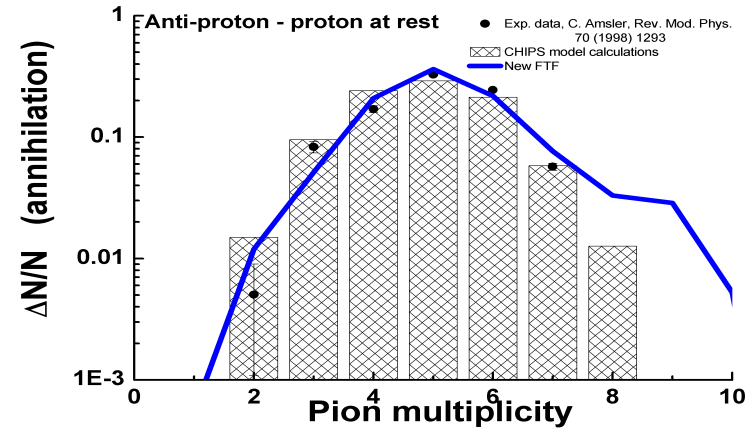
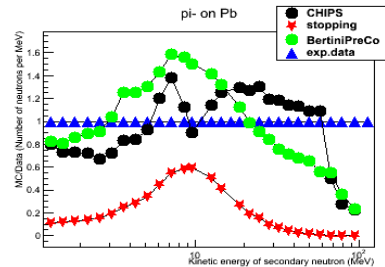
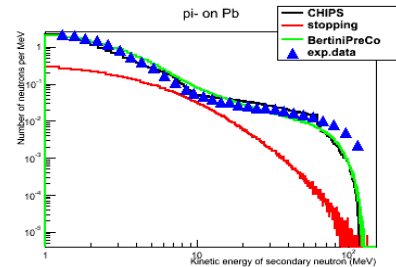
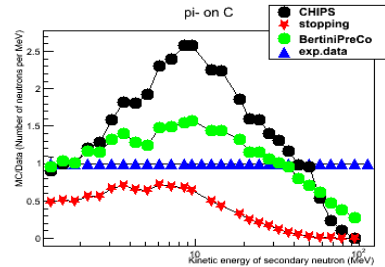
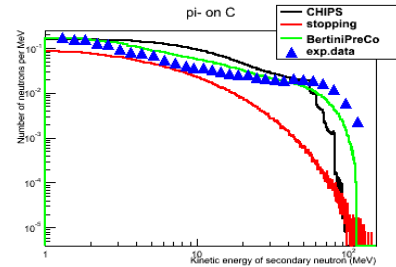


## Capture/Annihilation Models

- Current status:
  - Simplified (Gheisha-like) code - used for mu
  - CHIPS model - for all other particles
- New Development to replace CHIPS this year
  - Bertini(+Preco) for pi, K, Sigma
  - FTF for pbar; plans to extend for other anti-baryons and anti-nuclei
- Started work to restructure mu capture code



## Capture/Annihilation – pi-, K-, pbar



Data:  
R.Madey et al., Phys.Rev.  
C25, 3050-3067, 1982  
K.Larson et al., Phys.Rev.  
D47(3), p.47, 1993

## Other Available Models

- Low/High Energy Parametrized (LEP/HEP) models: earliest model in Geant4, port of Gheisha, fast but rough
- Quark Gluon String (QGS) model: an earlier alternative to FTF string model, current default high energy generator in production QGSP “family” of physics lists
- CHiral Invariant Phase Space (CHIPS) model: currently used for gamma-nuclear, nuclear capture of negatively charged hadrons, quasi-elastic in QGS, p-A and n-A elastic, kaon and hyperon nuclear cross sections
- Binary Cascade (BIC) model: theory-driven alternative to Bertini cascade, accurate at  $E_{kin} < 2\text{GeV}$

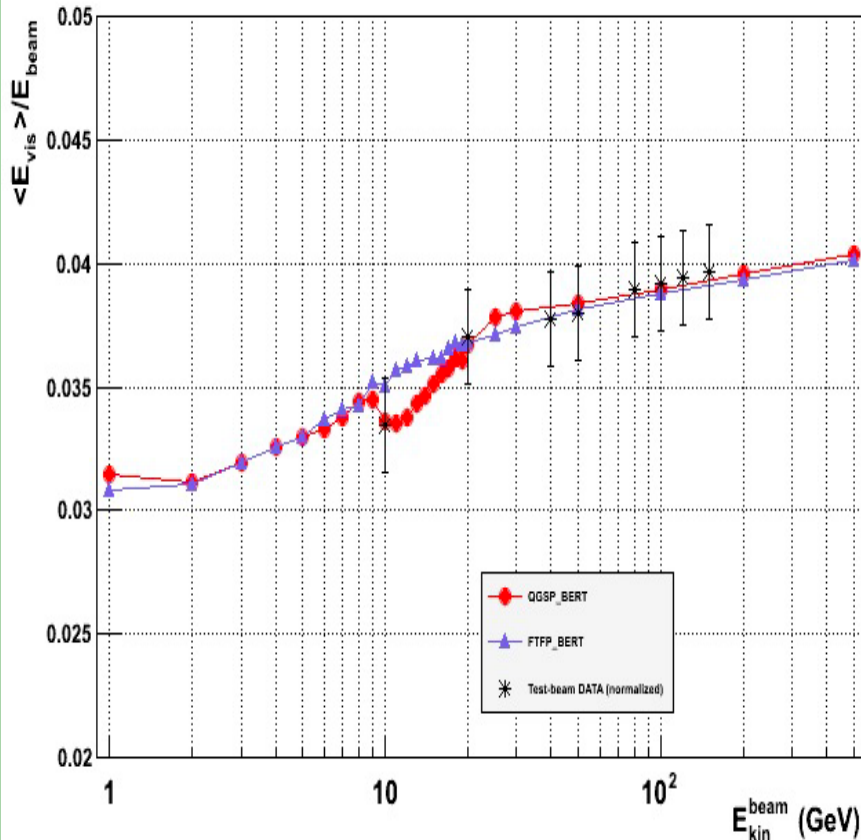


## Validation of Physics Lists: SimplifiedCalo Tests

- Stringent requirements are set by calorimeters
  - Typical observables: energy response, energy resolution, shower transverse and longitudinal shapes
  - Hadronic showers are most challenging
- Simplified geometry of calorimeters
  - ATLAS, CMS, LHCb
  - Zeus(compensating), CALICE (high granularity)
  - "Sandwich" geometry, no readout effects
- Frequent simulation to monitor developments
- Comparison vs data when available

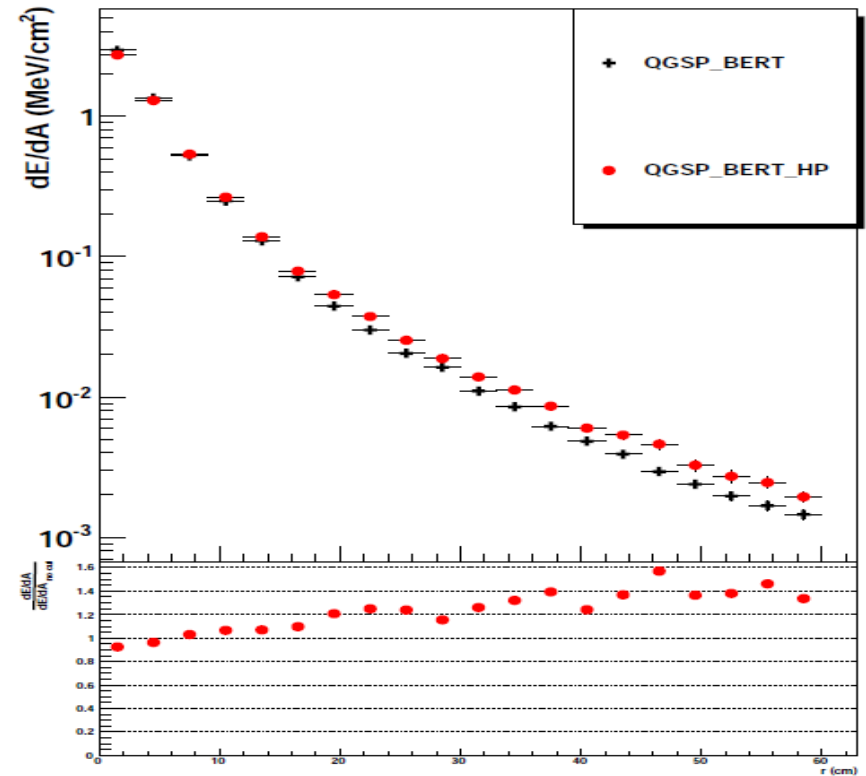
## pi- Beam on Sampling Calorimeter

Response



Cu / Liquid Ar  
Improvement with the use of FTF

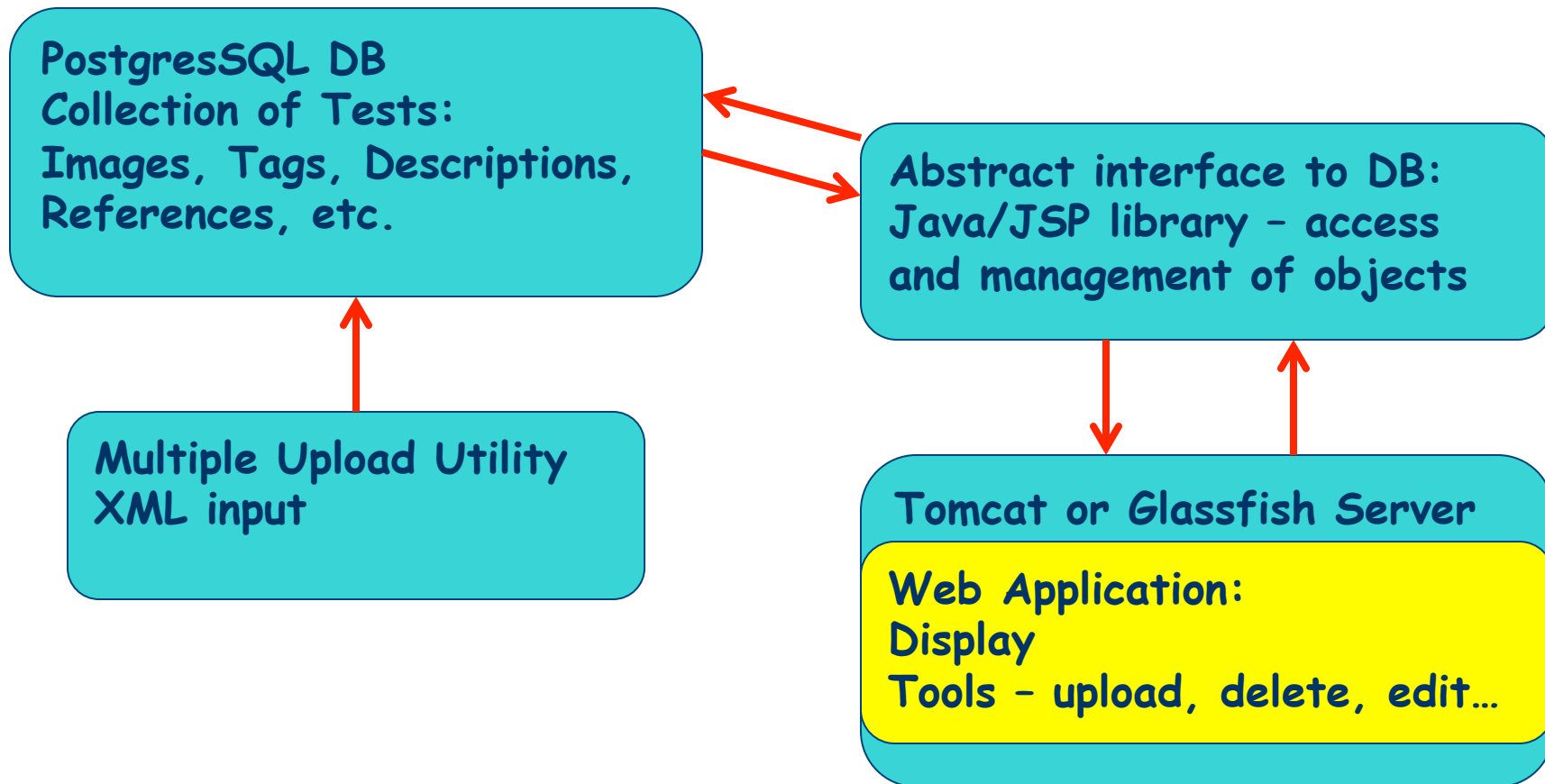
Radial Profile



Pb / Liquid Ar  
Improvement with the use of HP neutrons  
(wider transverse profile)

## Consolidation of Geant4 Validation Results (I)

New/improved models  $\longleftrightarrow$  increased number of comparison vs data



## Consolidation of Geant4 Validation Results (II)

<http://g4validation.fnal.gov:8080/G4HadronicValidation>

Geant4 Physics Validation - Mozilla Firefox

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Geant4 Physics Valid...

g4validation.fnal.gov:8080/G4HadronicValidation/G4ValHAD.jsp?TID=7620

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Home Validation Overview Electromagnetic Hadronic LHC-feedback Expert

**Name of the Test:** test48

**Responsible:** J. Yarba (Fermilab)

**Description:** Stopping particle test Monte Carlo predictions are compared to experimental data.

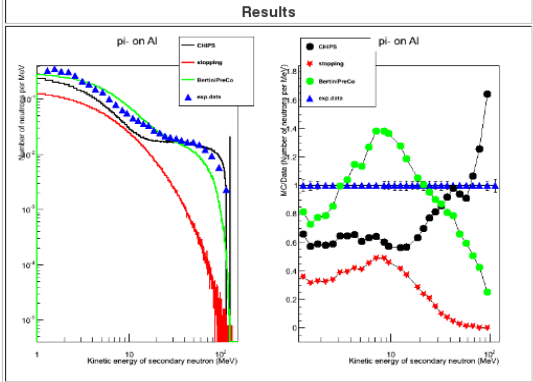
**Geant4 Version:** geant4-9.5-ref02

**Observable:** kinetic energy of secondary neutrons

**Reaction:** pi- on Al

Test Conditions	
Name	Description
Target	Al
Particle	pi-
Model	CHIPS, LEP, BertiniPrecompound
Reference	C. Amsler, Rev. Mod. Phys. 70, 1293 (1998)
Reference	C.B. Dover et al., Prog. Part. Nucl. Phys., Vol.29, pp.87-173 (1992)
Reference	R. Madey et al., Phys. Rev. C 25, 3050-3067 (1982)
Reference	K.D.Larson et al., Phys.Rev.D47(3), p.47, 1993
Score:	passed
Type:	expert

**Results**



**List of hadronic Tests**

- Hadrcap
- Ndata
- placeholder
- simplifiedCalo
- test30
- Test30iaea
- test35
- test45
- test47
- test48
- geant4-09-02-patch-01
- geant4-09-04-beta-01
- geant4-09-04-ref05
- geant4\_09\_05\_beta01
- geant4-9.4-ref10
- geant4-9.5-ref02

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## Summary

- Significant progress has been made in Geant4 Hadronic Physics, driven and validated with the data or feedback by past, present and proposed experiments
- Development concentrates on key models: FTF, BERT, Preco, HP neutrons
- Several production physics lists are provided; they are stable but not frozen, and aim to improve with feedback from experiments